Doi:doi.org/10.70693/cjst.v1i2.1334 Vol.1 No.2 2025

Structural Design Optimization and Circular Utilization Technology of Steel Hanging Plate of Bracket Bracings in Metro Tunnels Oriented by Sustainable Development

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Abstract: With the development of social economy, environmental problems have become prominent, and sustainable development has emerged as an important model. In the deep foundation pit projects of subway construction, steel supports are widely used. However, traditional corbel brackets have many disadvantages. This article is based on the Urumqi South Railway Station project and conducts an optimized design of the corbel bracket structure, adopting a square steel hanging plate, steel hooks, and a steel plate bottom bracket structure. Through research, the optimized design has significant advantages. It saves 174,000 yuan for the project, increases construction efficiency by 70%, and effectively reduces the risks of working at heights. It eliminates the welding process, is adjustable in position, and is convenient for construction. From the perspective of sustainable development, this design reduces steel consumption, can be reused, reduces resource input costs, reduces construction noise and dust pollution, realizes resource recycling, reduces maintenance costs, and enhances structural durability. It meets the requirements of economic, social, and environmental sustainable development and provides a useful reference for subway tunnel construction.

Keywords: improved corbel bracket; deep foundation pit; timeliness and safety; steel hanging plate

1. Introduction

Steel supports are currently a widely adopted form of retaining support in subway stations. Compared to concrete supports, they eliminate the need for curing time, allowing for immediate excavation and support, making them fast and efficient. They are widely used in foundation pit retention. Research has explored the selection and recycling of decoration materials in prefabricated buildings[1]. The economic value and impact of sustainable architecture have been analyzed[2]. Through literature review, the current state of research on environmental responsibility, social responsibility, and governance capacity in sustainability-related fields for major projects has been examined[3]. A systematic summary has been made regarding deformation control during foundation pit and underground engineering construction, along with strategies for engineering safety control[4]. Theory and engineering practice indicate that support stiffness is one of the key factors affecting foundation pit deformation[5-6]. Taking a certain foundation pit project of Shenzhen Metro as an example, numerical analyses were conducted on both concrete and steel supports using the finite element software ABAQUS, examining the variation patterns of axial forces in the supports and lateral displacement of the retaining walls at different excavation stages [7]. In conjunction with the deep foundation pit project of Xi'an Metro Line 5, detailed discussions were provided on the steps involved in steel support construction, including assembly, erection, preloading of axial force, and removal, along with specific control measures proposed[8]. If reinforced concrete supports are placed in the middle of the foundation pit, their compressive performance can be fully utilized, reducing deformation and bending moments in the retaining structure[9]. Triaxial tests were used to simulate the lateral unloading process of soil during foundation pit excavation, obtaining soil deformation parameters, and a finite element analysis was performed on an actual engineering case. The results showed that calculations based on soil deformation parameters obtained from lateral unloading triaxial tests were more consistent with measured data[10].

However, there remains a critical gap in existing research: most studies focus on macro-level issues such as the optimization of overall support stiffness, foundation pit deformation control, or material recycling strategies, while paying insufficient attention to the structural defects of corbel brackets—a key connecting component between steel walers and steel supports. Traditional corbel brackets have three unresolved pain points that restrict the sustainable and efficient execution of construction projects: First, the on-site welding of brackets to walers involves a heavy workload, takes a long time, lacks fixed operating platforms, and poses significant safety risks for high-altitude operations. Second, pre-welded brackets often fail to align with the actual centerline of the erected steel supports, leading to uneven stress distribution, severe axial force loss, increased deformation of walers, and thus endangering the stability of the foundation pit. Third, due to variations in support spacing across different projects, after the removal of steel supports, the brackets must be cut off, which damages the steel walers, shortens their reusable service life, and reduces construction efficiency. Existing research has not yet proposed targeted optimization schemes to address these three issues—efficiency, safety, and reusability—simultaneously, which has become a technical bottleneck for the sustainable development of deep foundation pit projects in subway construction.

Based on practical engineering experience and aiming to fill this research gap, this study takes the deep foundation pit project of Urumqi South Railway Station Metro as the research object to conduct structural optimization research on corbel brackets. The core objectives of this study include three aspects: 1) Develop an optimized bracket structure (integrating square steel hanging plates, steel hooks, and steel plate bottom brackets) to eliminate on-site welding operations, reduce the risks of high-altitude operations, and improve construction efficiency; 2) Realize adjustable bracket positions and reusability, thereby reducing steel consumption, avoiding damage to steel walers, and lowering resource input costs; 3) Reduce construction noise and dust pollution through structural simplification, while enhancing structural durability to meet the economic, social, and environmental requirements of sustainable development. Ultimately, this study aims to provide practical technical references for the efficient, safe, and sustainable application of steel support brackets in deep foundation pit projects of subway tunnels.

2. Overview of the Deep Foundation Pit Support System

The Urumqi South Railway Station in Xinjiang is oriented in a north-south direction, situated beneath Nanzhan Road and to the west of Yashan North Road. The station is an underground three-story island-type platform with a total length of 165 meters. The effective center mileage is K9+ 530.179, the width of the standard section is 23.3 meters, and the total width at the ends of the station is 28.5 meters. The depth of the base plate at the centerline is buried 26.16 meters below ground level, and the main building area of the station spans 13,308 square meters.

The retaining structure of the station is designed in the form of bored piles combined with internal supports. In total, there are 239 steel supports. The support system consists of crown beams, steel supports, and steel walings. The foundation pit of the station is equipped with five layers of supports (with the second-layer support partially omitted). Additionally, two concrete supports have been added at the top of the northwest corner of the foundation pit.

There are two types of internal supports for the retaining structure. The first type is a concrete support, used for the first-layer support. The second type consists of a steel support combined with a steel waler, primarily utilized for the second, third, fourth, and fifth layers of internal supports. The steel pipe used for the internal supports has a diameter of Φ609 and a wall thickness of 16mm. The steel walings are fabricated by welding hot-rolled H-shaped steel HM500×300a with flange connection plates. The steel supports are braced against the steel walings. To ensure structural stability, the fixed ends and adjustable ends of the supports must be staggered both horizontally and longitudinally.

Fig. 1 Bird's - eye view of Urumqi South Railway Station of the Metro

Table 1 Steel Support Statistical Table

Serial number	part	form	Material (mm)	horizontal spacing (m)	vertical spacing (m)
1	The first support	Concrete	C35	9	4.45
2	The second support	Steel supportQ235	Φ609, t= 16	3	5
3	The third support	Steel supportQ235	Φ609, t= 16	3	6.5
4	The fourth support	Steel supportQ235	Φ609, t= 16	3	5.5
5	The fifth support	Steel supportQ235	Φ609, t= 16	3	3.78

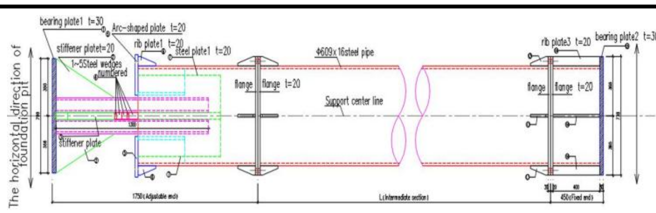

Fig. 2 Plan Design Diagram of Steel Support Assembly

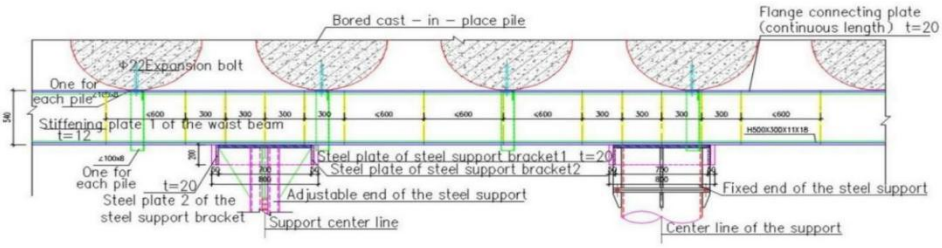

Fig. 3 Plan Design Diagram of Steel Waist Beam (Cross - Brace Section)

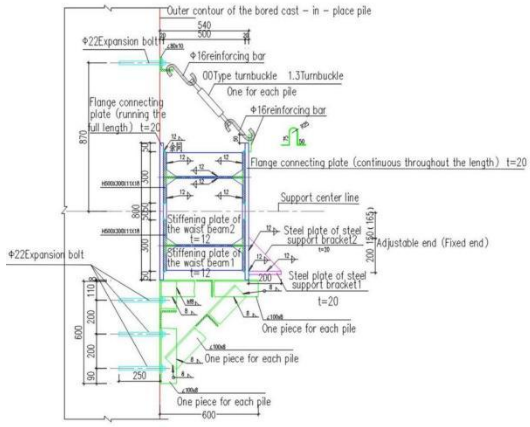

Fig. 4 Design Profile Diagram of Steel Support Bracket Steel Plate

3. Design ideas for research methods

This construction technology can provide a kind of turnover material, which has the characteristics of simple construction technology, single process, cost-saving, and high turnover times.

There are 239 steel supports in this station. The welding workload of the steel support brackets is relatively large. In order to ensure the construction progress and save the construction cost, after conducting a comprehensive on-site investigation, discussions within the project department, self-evaluation, and comparative analysis, it was decided to use square steel hanging plates instead of steel cantilever brackets for the steel supports. This can not only save the overall project cost, improve the utilization rate of steel, but also shorten the overall construction period. The design flowchart of the research methodology is shown as follows.

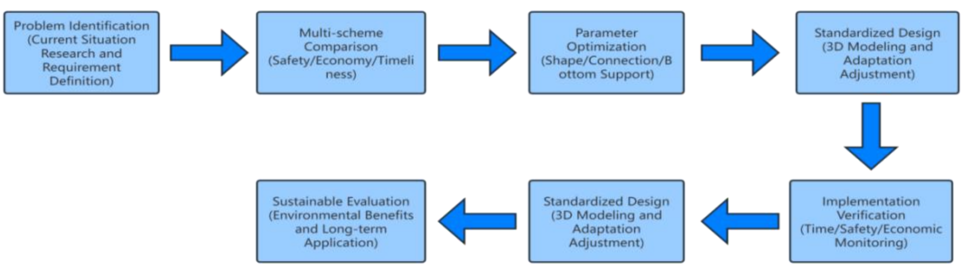

Fig. 5 Methodology Design Diagram

4. Design and Analysis Research of the Steel Bracket Structure

4.1Analysis and Research on the Erection Time of Traditional Steel Supports

In this project, 10 steel supports were randomly selected and numbered GZC1-GZC10 in the order of selection. The total erection time of each steel support and the average construction time of each process were counted and sorted out, as shown in Figure 6 and Figure 7.

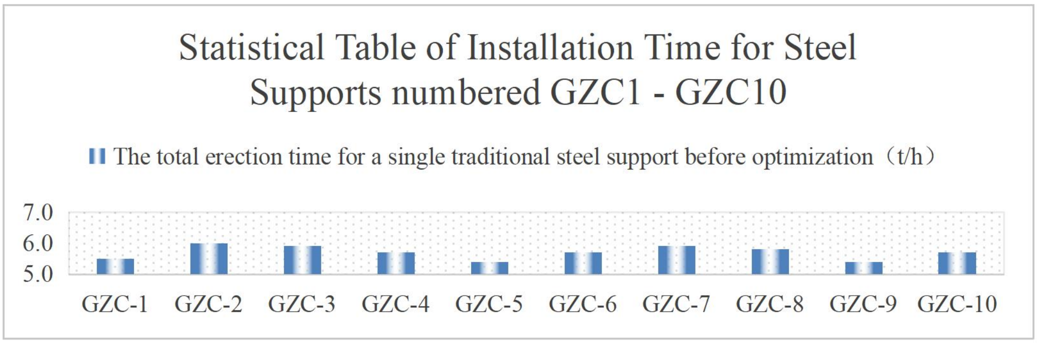

Fig. 6 Construction Time of Single Steel Support Erection

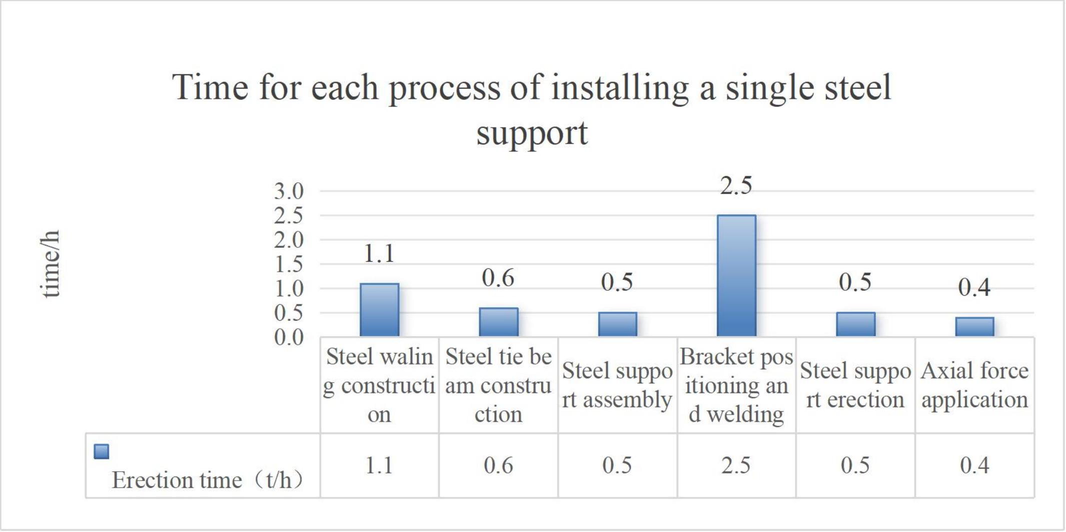

Fig. 7 Average Construction Time of Each Process in Single Steel Support Erection

It can be seen from Figure 5 that the average construction time of the steel support is 5.7h, which exceeds the expected construction time of 4h for the steel support, resulting in a lag in the overall progress. It can be seen from Figure 6 that the positioning and welding of the cantilever bracket take the longest time among all processes. In order to shorten the erection time of the steel support, by observing the construction time of each process, it is concluded that the positioning and welding time of the cantilever bracket should be compressed to reach the expected construction time.

4.2 Design and Analysis Research of the Connection Structure

In order to speed up the construction progress and complete the node construction period, it is urgent to design a hanging plate that is movable, easy to disassemble and assemble, safe and reliable, and does not affect the strengthening of the waling stiffness.

According to past construction experience of steel supports and combined with the actual on - site situation, three schemes, namely the hanging plate method, the welding method, and the bolt method, were proposed. A comparative analysis was carried out on the safety, timeliness, economy (calculated by unit price), and reliability of the three schemes, as shown in Table 7. It can be seen from the table that the hanging plate method is convenient and simple for construction, takes a short time, and has low processing costs; the welding method has a large amount of construction work, low efficiency, and high costs; the bolt method is convenient and simple for construction, takes a short time, and has low processing costs, but it seriously damages the steel waling. After comprehensive consideration, the hanging plate method was selected as the fixing method for the steel lacing plate.

Table 2 Scheme Comparison Table

Plan	Technical characteristics	Security	take time/h	Economy (RMB)	Reliability
Steel corbel welding method	Manually weld the bracket of the corbel to the steel waling, requiring full welding to integrate it with the steel waling.	Low safety	2.5-3	310	The workload is large, the efficiency is low, the positioning is complicated, and the displacement is difficult.
Steel hanging plate method	The hanging plate can be moved. There is no lifting hole at the top. It is integrated with the steel waling through hooks.	Tests are needed. High safety.	≤1	180	The displacement is flexible, and it can be processed by using existing resources. It is simple and easy to implement.
Bolt method	Both components need to be perforated and integrated with the steel waling using bolts, allowing for flexible displacement.	Tests are needed. High safety.	≤1	180	The displacement is flexible, but the steel waling is severely damaged, which affects the service life.

4.3 Design and Analysis Research of the Shape Structure

In order to ensure that all the stress after the steel support applies the axial force acts on the hanging plate, the selection of the hanging plate type was determined through the analysis of safety, timeliness, economy, and reliability, as shown in Table 3.

Table3 Hanging Plate Shape Comparison Table

Plan	Safety	Timeliness	economy（RMB）	Reliability
square	The safety level is relatively high.	The processing is simple and can be carried out by utilizing existing resources.	35	It has strong operability and a high utilization rate of raw materials.
circle	The safety level is relatively high.	The processing is simple and can be carried out by utilizing existing resources.	60	However, it has high requirements for processing equipment and personnel skills, and consumes a large amount of materials.

It can be seen from Table 3 that the square hanging plate has a low cost, is convenient for processing, and has a high utilization rate of raw materials. The circular hanging plate has a slightly higher cost, is more complex to process, and consumes a large amount of materials. Therefore, after comprehensive comparison, the square steel hanging plate was selected.

4.4 Design and Analysis Research on the Material of the Hook Connection

The hanging plate needs to be connected to the steel waling through a hook. The selection of the hook directly affects the construction efficiency and safety. Two types of hooks, namely steel and bolt, were proposed, and their safety, economy, and reliability were compared, as shown in Table 9. It can be seen from Table 9 that both the steel hook and the bolt hook have high safety, but due to the high cost of the bolt hook, the steel hook was selected.

Table 4 Hook Comparison Table

Plan	Safety	Cost (RMB)	Reliability
steel - made	There is a relatively high requirement for the quality of welds. The strength meets the requirements, ensuring a high level of safety.	68	The processing is relatively complex, but it can be processed by making use of existing resources.
bolt	There are relatively high requirements for the quality of bolts. Their strength meets the requirements, ensuring high safety.	155	The processing is relatively complex, but it can be processed by making use of existing resources.

4.5 Design and Analysis Research on the Material of the Bottom Bracket

In order to keep the elevations at both ends of the steel support consistent, it is necessary to add a bottom bracket at the bottom of the hanging plate. Two schemes, namely the steel plate bottom bracket and the steel hook bottom bracket, were proposed, and their safety, economy, and reliability were compared, as shown in Table 10. It can be seen from Table 10 that the steel plate bottom bracket has a low processing cost, high safety, is convenient for construction, and can effectively prevent the steel support from rolling; the steel hook bottom bracket has a low processing cost, but low safety and poor construction reliability. The hook cannot accurately hold the steel support. Therefore, the steel plate bottom bracket was selected.

Table 5: Bottom Bracket Comparison Table

Plan	Safety	Cost（RMB）	Reliability
steel plate	The strength meets the requirements, ensuring high safety.	80	Adding rib plates on both sides of the hanging plate effectively prevents the steel support from rolling. It can be processed using existing resources and is convenient to use.
steel hook	The bottom bracket bears shear force, with changeable conditions. The safety level is relatively low, and the support is prone to rolling.	65	Since the fixed ends of the steel supports are all circular, the hooks cannot accurately catch the steel supports, resulting in poor construction reliability.

4.6 Conclusion of the Design and Analysis of the Steel Bracket Structure

Finally, through the optimization of the scheme, a square steel hanging plate structure was obtained. The three-view drawings of the structure are shown in Figure 6-8. It is applicable to steel supports with a diameter of 800mm. For steel supports with a diameter of 609mm, the side length of the steel lacing plate can be changed to 750mm. For steel supports equipped with axial force gauges, the steel plate bottom bracket can be extended to 500mm.

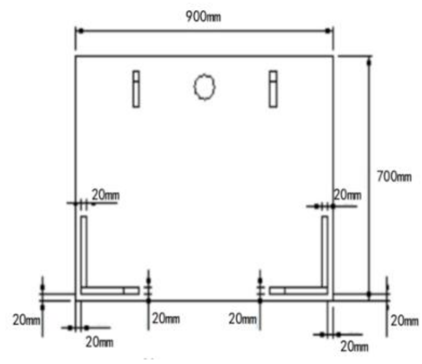

Fig. 8 Front View Design Diagram of the Steel Hanging Plate

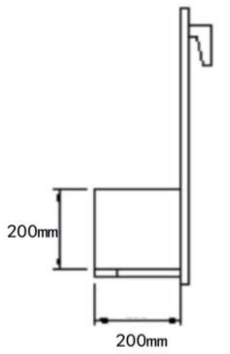

Fig. 9 Side View Design Diagram of the Steel Hanging Plate

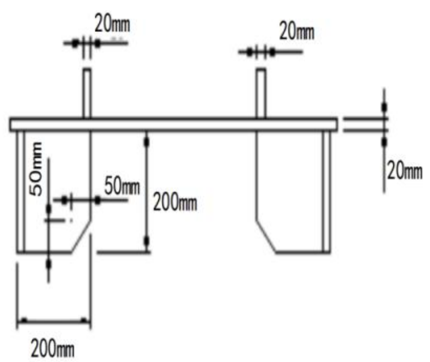

Fig. 10 Top View Design Diagram of the Steel Hanging Plate

5 Analysis of the Implementation Effect after the Optimization Design

After the new-type square steel hanging plate was processed according to the design, a test was carried out in the foundation pit of the Urumqi South Railway Station. The results show that the optimized square steel hanging plate is convenient and fast to use, improves the installation and removal efficiency of the steel support, avoids the phenomenon of axial force loss, has good safety performance, and improves the construction efficiency.

5.1 On-site Implementation Effect Diagram

The steel support hanging plates are placed in advance before the erection of the steel support. After hanging, the steel support is directly hoisted and placed on the hanging plates of the two - side walings, and then pressurized.

Fig. 11 Implementation Effect Diagram 1 of the Steel Hanging Plate for Improving the Cantilever Bracket

Fig. 12 Implementation Effect Diagram 2 of the Steel Hanging Plate for Improving the Cantilever Bracket

5.2 Test and Detection of the Improved Support System

Through the test and inspection of the pile integrity, steel supports, and steel wales in the retaining structure support system of the South Railway Station, all meet the specifications and on-site requirements.

(1) Detection of Pile Integrity of the Support System's Pile Foundation

Compliance of the testing institution's qualifications: The pile integrity testing this time was carried out by Xinjiang Liufang Building Technology Research Institute (Co., Ltd.). This institution holds a Qualification Accreditation and Metrology Certification Certificate (No.: 2015310025M) and a Xinjiang Construction Engineering Quality Testing Institution Qualification Certificate (No.: Xinjiang Jianzi 2015010209). During the testing process, it strictly followed relevant specifications, with full legality and compliance.

Good pile integrity: According to the test report, all key indicators of the tested piles, including pile body wave velocity, reflected wave characteristics, etc., meet the engineering design and actual use requirements, and the pile integrity is in good condition.

(2) Detection of Steel Supports in the Support System

Compliance of the testing basis: The testing work of the steel supports for the South Railway Station of the first-phase project of Urumqi Rail Transit Line 3 was carried out in an orderly manner in strict accordance with relevant standard specifications and entrusted requirements. Xinjiang Liufang Building Technology Research Institute (Co., Ltd.), which undertakes the testing task, with its Qualification Accreditation and Metrology Certification Certificate (No.: 2015310025M) and Xinjiang Construction

Engineering Quality Testing Institution Qualification Certificate (No.: Xinjiang Jianzi 2015010209), ensures the standardization and legality of the testing process.

Qualified quality of steel supports: According to the test report [2017] Xinke Quality Inspection Word No. LF2017036237, all indicators of the tested steel supports, such as material properties, dimensional deviations, and mechanical properties, meet the engineering design standards and actual use requirements and can be applied to this engineering construction project.

5.3 Stress Monitoring of the Improved Support System

Through the analysis of various monitoring data of the improved steel support system for the foundation pit of the steel hanging plate of the bracket of the corbel, including ground surface settlement, pipeline settlement, settlement of surrounding buildings, horizontal displacement at the top of the retaining pile (wall), vertical displacement at the top of the retaining pile, horizontal displacement of the retaining pile body, horizontal displacement of the column structure, vertical displacement of the column structure, support axial force, and groundwater level, the current engineering construction is in a safe state. The construction has little impact on the surrounding environment and the engineering structure itself, and normal construction can be carried out. However, it is still necessary to continue monitoring according to the established monitoring frequency and methods to timely detect potential problems and take corresponding measures.

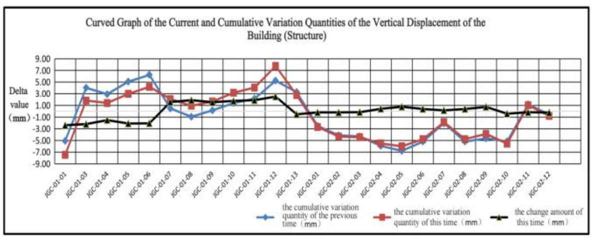

Fig. 13 Curved Graph of the Current and Cumulative Variation Quantities of the Vertical Displacement of the Building (Structure)

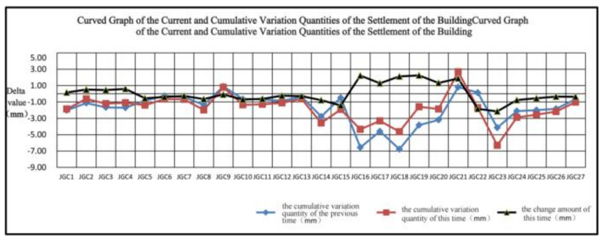

Fig. 14 Curved Graph of the Current and Cumulative Variation Quantities of the Settlement of the Building Curved Graph of the Current and Cumulative Variation Quantities of the Settlement of the Building

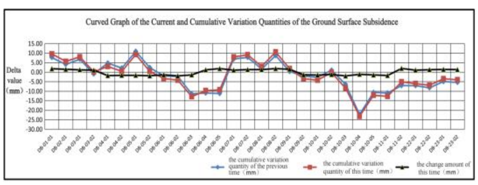

Fig. 15 Curved Graph of the Current and Cumulative Variation Quantities of the Ground Surface Subsidence

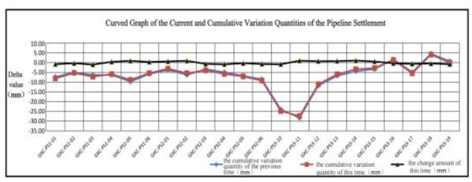

Fig. 16 Curved Graph of the Current and Cumulative Variation Quantities of the Pipeline Settlement

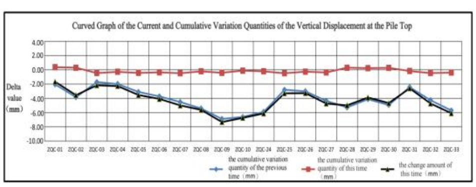

Fig. 17 Curved Graph of the Current and Cumulative

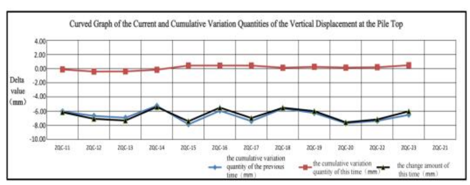

Fig.18 Curved Graph of the Current and Cumulative

Variation Quantities of the Vertical Displacement at the Pile Top

Variation Quantities of the Vertical Displacement at the Pile Top

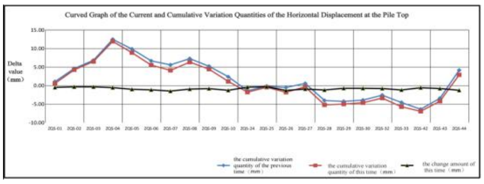

Fig. 19 Curved Graph of the Current and Cumulative Variation Quantities of the Horizontal Displacement at the Pile Top

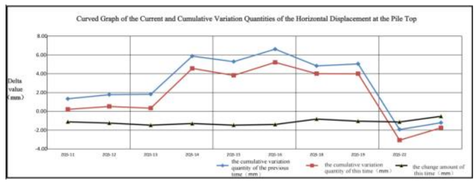

Fig. 20 Curved Graph of the Current and Cumulative Variation Quantities of the Horizontal Displacement at the Pile Top

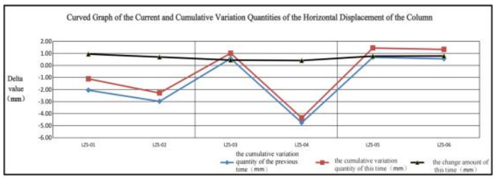

Fig. 21 Curved Graph of the Current and Cumulative Variation Quantities of the Horizontal Displacement of the Column

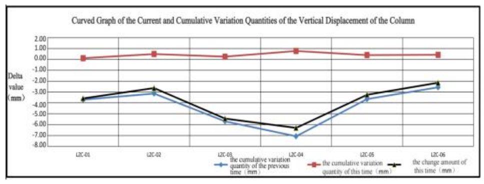

Fig. 22 Curved Graph of the Current and Cumulative Variation Quantities of the Vertical Displacement of the Column

5.4 Time - related Benefits

During the test, 10 steel supports were randomly selected and numbered GZC1-GZC10 in the order of selection. The total construction time of each steel support, the average construction time of each process, and the time analysis table before and after optimization were counted and sorted out.

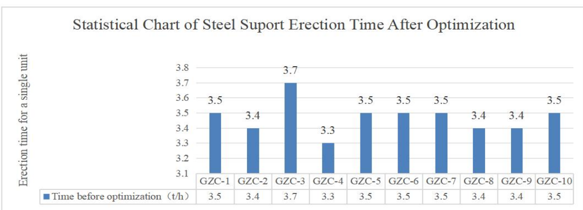

Fig. 23 Construction Time of Single Steel Support Erection after Optimization

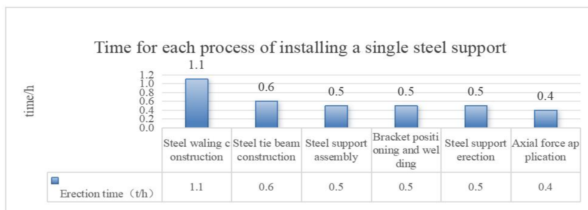

Fig. 24 Construction Time of Each Process in Steel Support Erection after Optimization

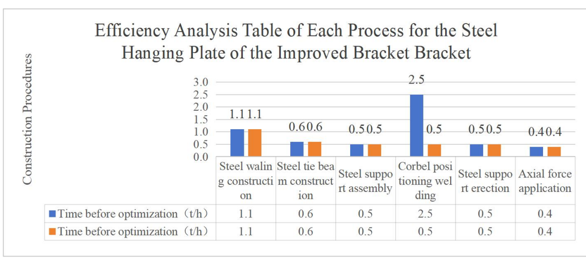

Fig. 25 Efficiency Analysis Table of Each Process of the Steel Hanging Plate for Improving the Cantilever Bracket

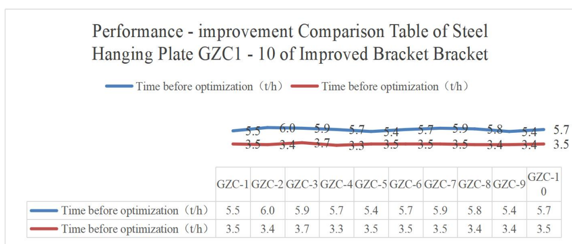

Fig. 26 Efficiency - increasing Comparison Table of GZC1-10 of the Steel Hanging Plate for Improving the Cantilever Bracket

It can be seen from Figure 23-26that the use of the optimized steel hanging plate improves the erection efficiency of the steel support, speeds up the construction progress, shortens the construction period from the original 2.53h to 0.5h, and achieves the expected effect. At the same time, it solves the problem that the center lines of the original steel cantilever bracket and the steel support do not coincide, and eliminates the potential safety hazards in the foundation pit support.

5.5 Economic Benefits

The application of the new-type steel hanging plate improves the erection efficiency of the steel support and shortens the construction period, achieving good economic benefits. Through cost accounting, one steel cantilever bracket requires 37.68 kg of 20-mm-thick steel plate. 478 steel cantilever brackets require a total of 18t of steel plate. One steel cantilever bracket requires a welder to weld for 2 hours, and 3 hours for disassembly and repair, a total of 5 hours for a welder. 478 steel cantilever brackets require 2,390 hours of welders, that is, 299 man-days. At present, the price of steel in the Urumqi area is 4,700 yuan per ton, and the wage of a welder is 300 yuan per day. A total of 18×4,700+299×300=174,000 yuan is directly saved in cost.

6.Conclusion

(1) Economic Benefits

In the Urumqi South Railway Station project, the optimized square steel hanging plate cuts steel consumption and welding work, directly saving 299 welder workdays and 174,000 yuan. Its reusability lowers long-term resource costs, boosting the project’s economic viability and aligning with economic sustainability.

(2)Social Advantages

It reduces high-altitude operation risks, protecting construction workers, safety and well-being, and builds a safe working environment. With 70% higher construction efficiency, the project period is shortened, minimizing impacts on nearby residents, lives and traffic, thus easing congestion and maintaining social stability.

(3) Environmental Contributions

The simple-structured hanging plate generates less noise and dust during installation and disassembly, reducing construction pollution and ecosystem interference.As a reusable material, it lessens environmental pressure from new resource exploitation, realizing resource recycling and complying with environmental sustainability.

(4)Sustainability Improvements

Unlike traditional steel supports (prone to weld cracking and high maintenance costs), the modular hanging plate only needs regular bolt checks, slashing maintenance processes and unit costs while reducing unexpected maintenance needs. Made of high-quality steel with anti-corrosion coatings, it has strong corrosion resistance. Its rectangular cross-section ensures uniform stress (reducing fatigue), and modular design allows replacing only damaged parts, ensuring long-term structural performance for subway project safety and stability.

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